Cooperative Processing in Sensor Networks

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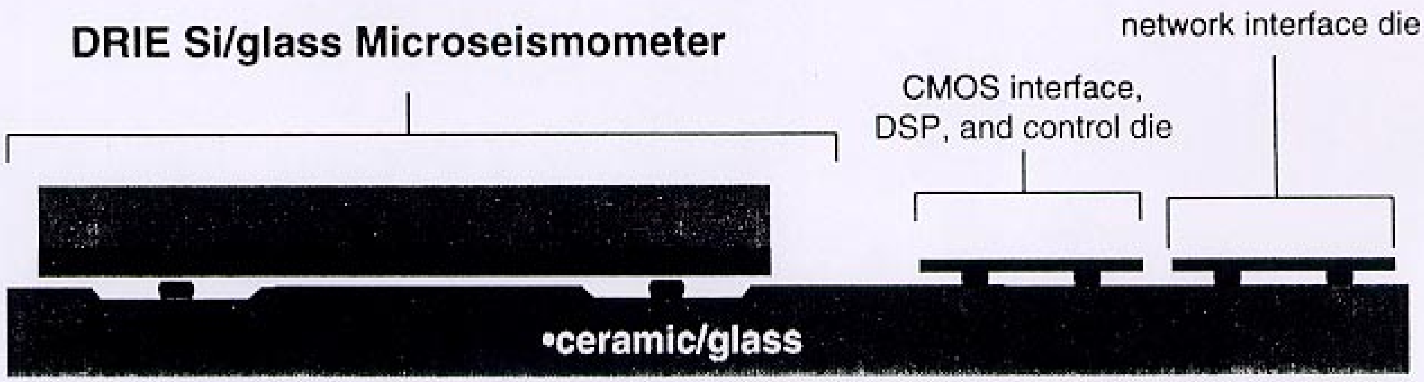
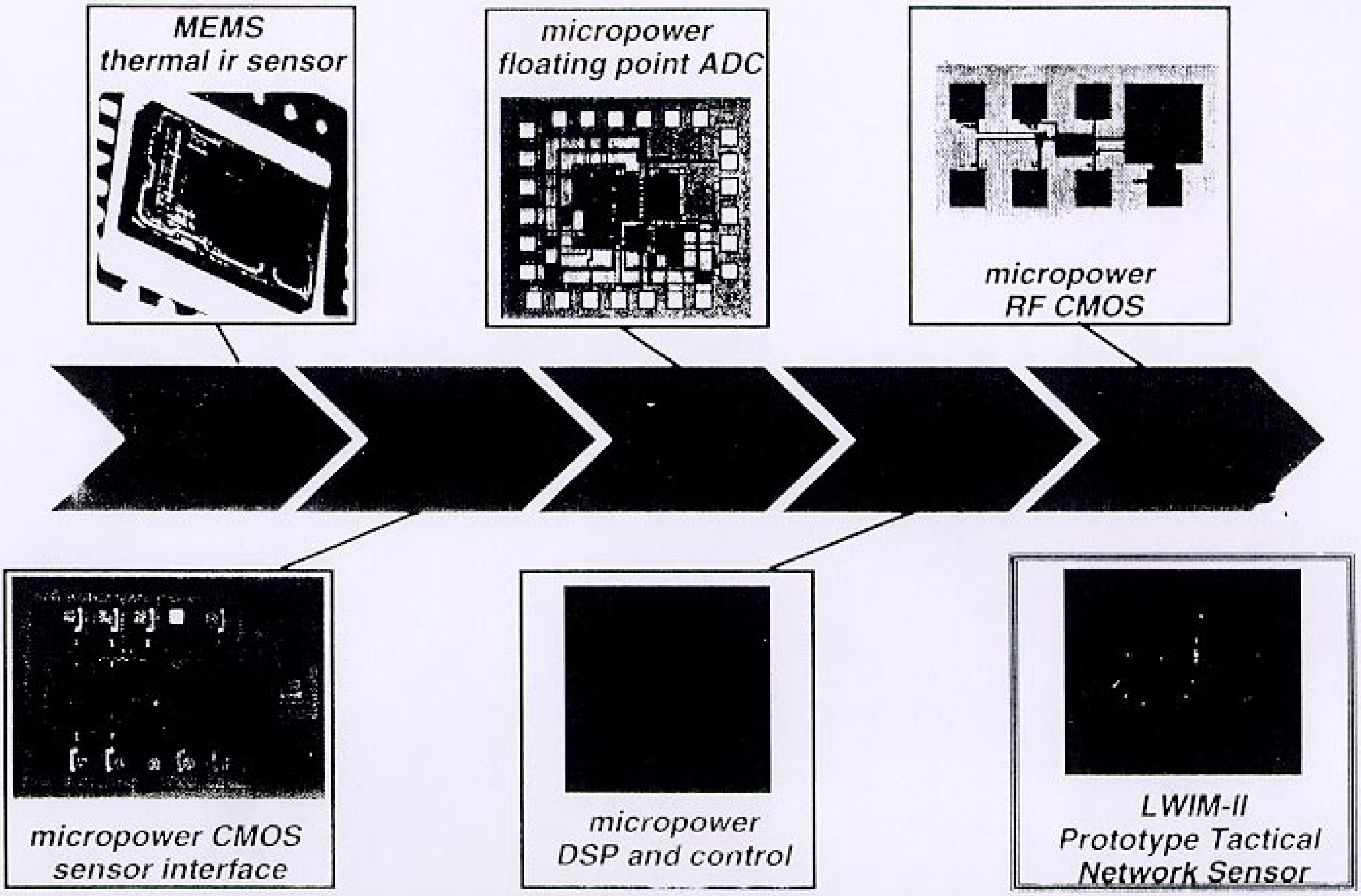
CIMS: Standard Cell MEMS

- CMOS Integrated Microsystems (CIMS)
- "standard cell MEMS", standard cell electronic components, "sensorstrate"
- standard packaging and materials processes
- diverse capability: seismic, ir, magnetic, etc.
- MCNC co-development and pilot production



Low Power Wireless MEMS



Adaptive Wireless Arrays for Interactive RSTA in SUO (AWAIRS)

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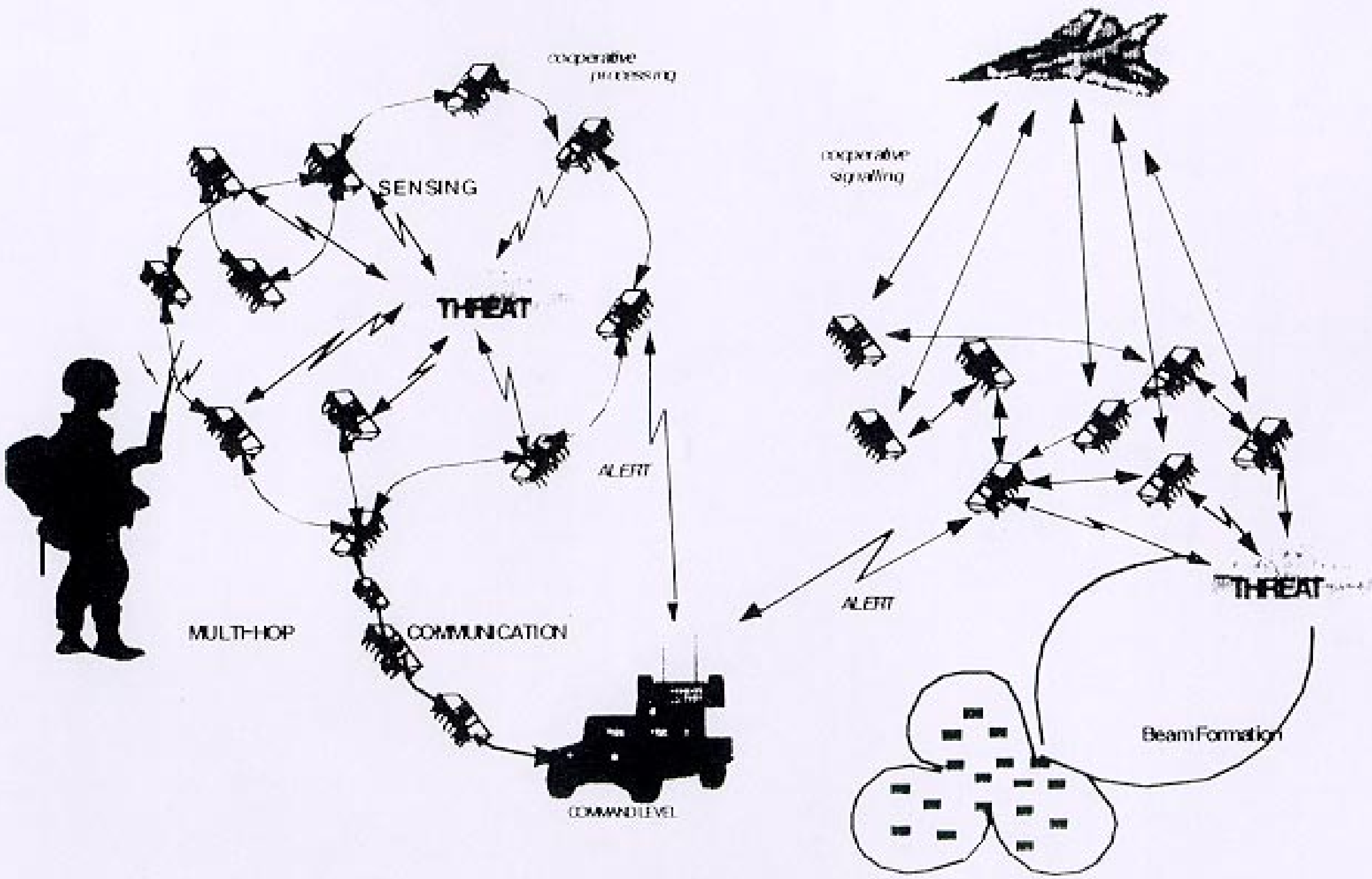

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Program Goals

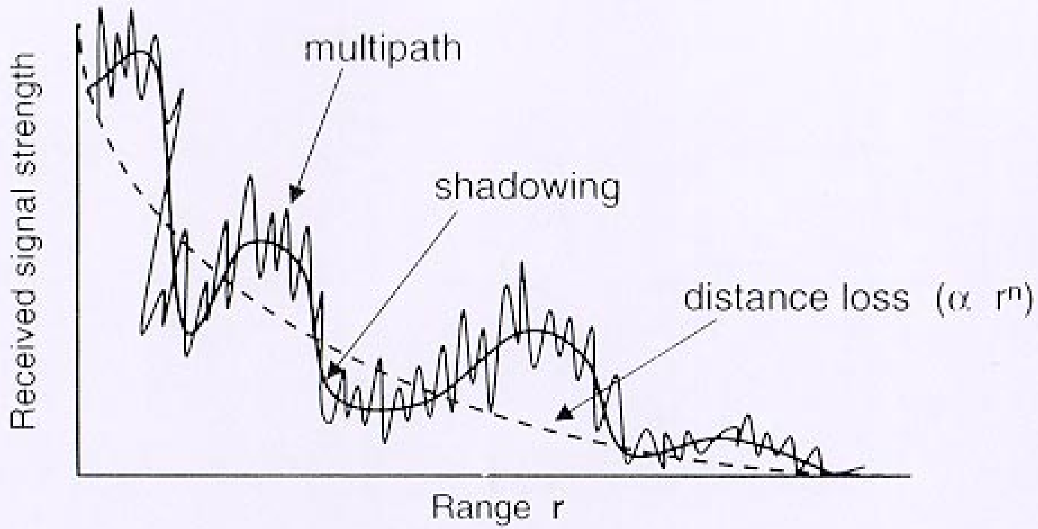
AWAIRS

- General interface pads for wide range of sensors
- Processor and operating system for low power
- Low-power circuits for cooperative processing functions
- Self-organizing, variable topology network
- Distributed synchronization and location algorithms
- Cooperative data fusion, beamformation, and communication
- Parallel simulation to evaluate extension to thousands of nodes
- Integration into demonstration network of small nodes

Distributed Information Processing

- Energy costs drive design for sensor nodes; RF communications is most costly component
- Reduce communication cost by extensive processing at source, turning on sensors only when need indicated, and sending messages only when something of interest has occurred.
- Establish networks to minimize the communication costs (multi-hopping, data fusion and sorting rather than simple relay) vs. simply maximizing communications throughput
- Beamforming and cooperative communications with randomly placed nodes; local rather than global communications to enable these functions.

Distance Loss, Shadowing, Multipath



- Deal with distance loss and shadowing using macro diversity, power control, variable transmission rate
- Deal with multipath using diversity, variable transmission rate

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Diversity Techniques

AWAIRS

- Multipath fading independent for sufficient separation in time, frequency, or space
- Diversity techniques can make up for most of multipath loss:

Rayleigh fading	$P(e) \propto 1/\gamma$
Diversity L	$P(e) \propto 1/\gamma^{L}$
Gaussian channel	$P(e) \propto \exp(-\gamma)$

- Macro diversity: different distance attenuation, shadowing for different receivers
- Combination leads to large power savings for bit rate / error rate target

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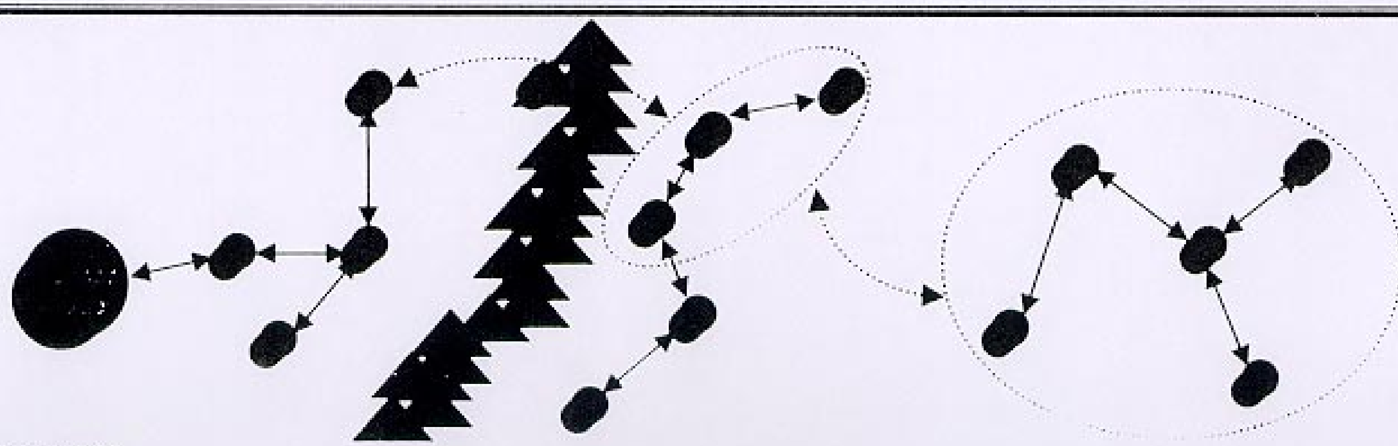
AWAIRS

AWAIRS RF Challenges

- Radio design -- low power essential, requires diversity
- Ground propagation -- not well characterized
- Antenna design -- interaction with packaging, environment
- Network topology -- establish routing to minimize power consumption (radiated power plus up/down conversion)

AWAIRS RF Communications

- Frequency hopping with coding ⇨ frequency diversity
- Multi-hop networks ⇨ macro diversity
- Two-way communication ⇨ enables power control, synchronous network
- Integrated radio with passive RF components ⇨ low power up- and down- conversion
- Cooperative communications ⇨ deals with random placement of nodes, terrain features



Detection and Estimation Problems

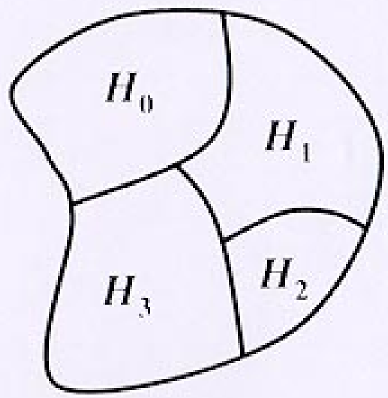
- **Bayes Estimation**

  Observation vector x

  Hypotheses $H_0, H_1, \ldots$

  Partition observation space; decide H_i if

  $$P(X|H_i) > P(X|H_k) \qquad k \neq i$$



Decision space

- This reduces to set of threshold tests
- Accuracy of estimates improves with SNR, length of observation time; Cramer-Rao bound establishes fundamental limits

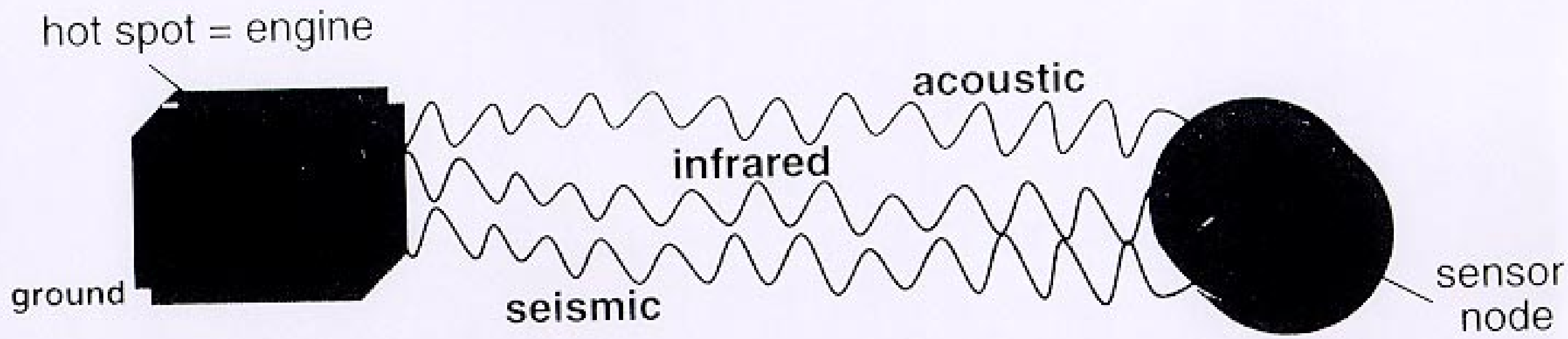
Target Detection

- For low power implementation, limit dimensionality of observation vector; performance complexity trade-off (e.g. energy vs. spectrum)

- Sieismic detection:
  - earth is low pass filter
  - generates broadband seismic noise
  - signature of target is range-dependent, and eventually undetectable

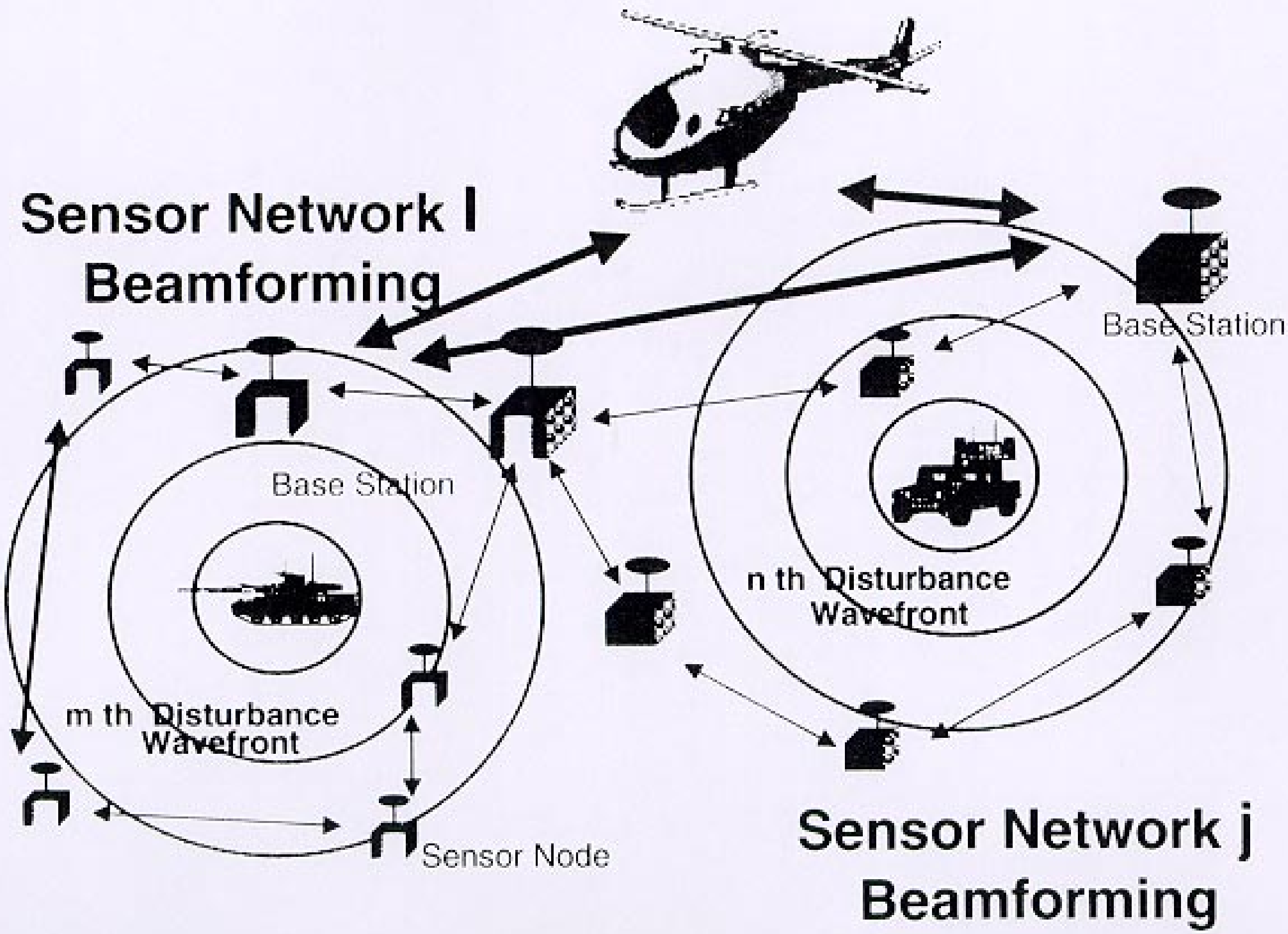
- Basic approach: try to find features which distinguish target from background / other targets
  - use orthogonal transformations (Fourier, wavelet)
  - best approach application-specific

Data Fusion



- Simple features in multiple domains may give more reliable detection than complex processing in one
- Multiple nodes can average over independent noise if signals dependent
- To save power, one may cue the others

Cooperative Signal Processing for Beamforming



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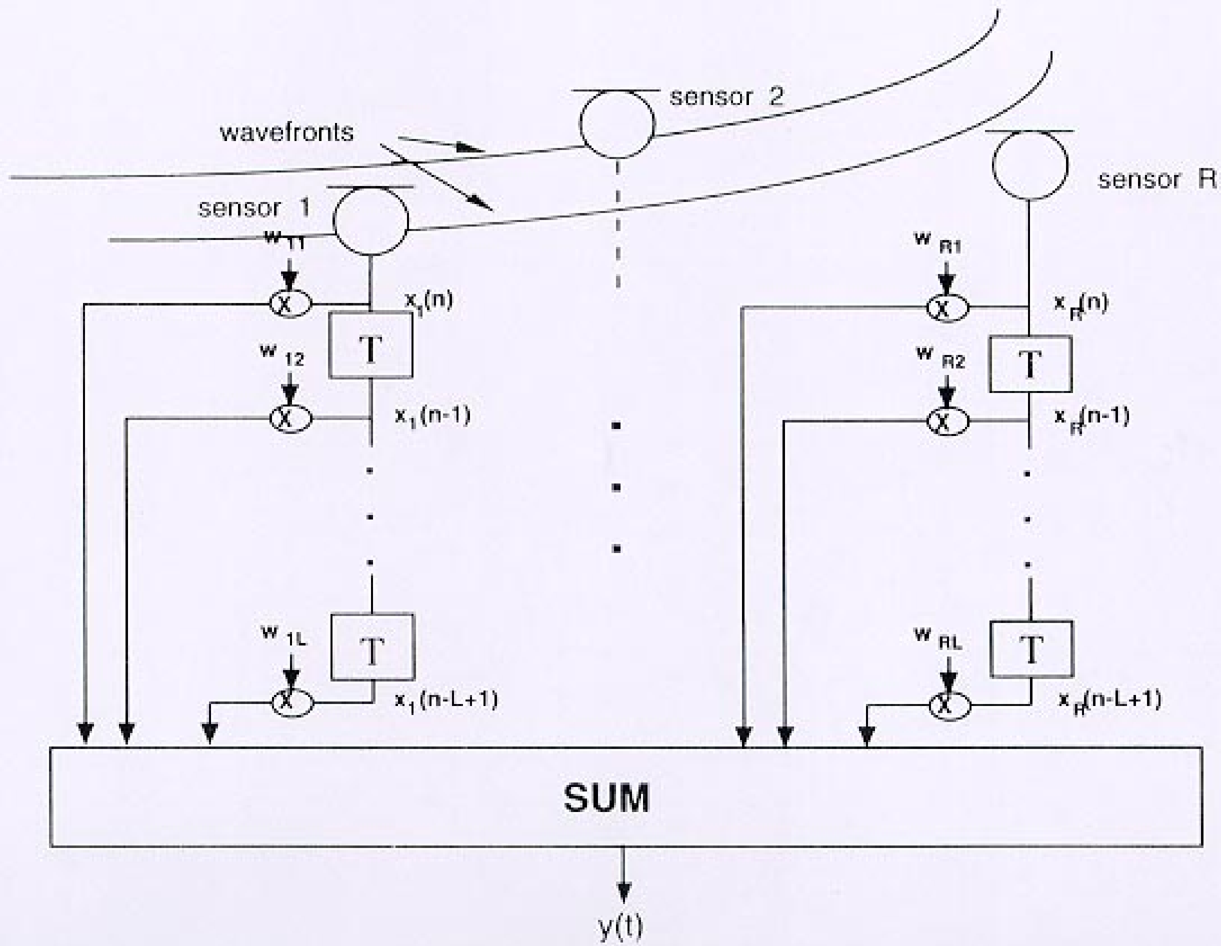
Basic Array and Processing Issues

AWAIRS

- Array beamforming using fixed sensor location has been used successfully in sonar / radar / emitter location applications
- Factors complicating beamformation in the new scenario:

1. Randomly distributed vs. fixed sensors
2. Sidelobe / interference reduction vs. mainlobe concentration
3. Near vs. far field
4. Broadband vs. narrowband sources
5. Diverse classes of sources
6. Diverse classes of sensors

Beamformer with R Sensors Using L Taps/Sensor



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Robust Sensor Array

AWAIRS

- Locations of sources and sensors are unknown but fixed
- Sensors' spatial / frequency responses are unknown
- Signal may be narrowband or broadband
- Signal characteristics are unknown
- Proposed algorithms need to be robust with respect to parameter uncertainties

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Adaptive Signal Enhancement Array

- The largest array output power is attained by coherently summing the strongest signal from all the sensors

- Maximize $w' R_x w$ subject to $w'w = 1$

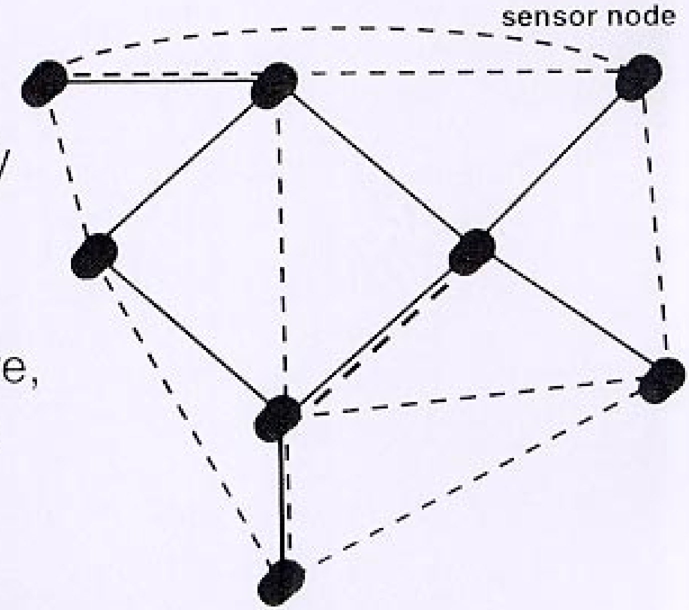
- Space-time beamformer weights are given adaptively by eigenvector w_1 of the largest eigenvalue λ_1 of $R_x w_1 = \lambda_1 w_1$ based on the $RL \times RL$ sample correlation matrix given by

$$\hat{R}_x(n) = \frac{1}{N} \sum_{k=0}^{N-1} x(n-k) x(n-k)'$$

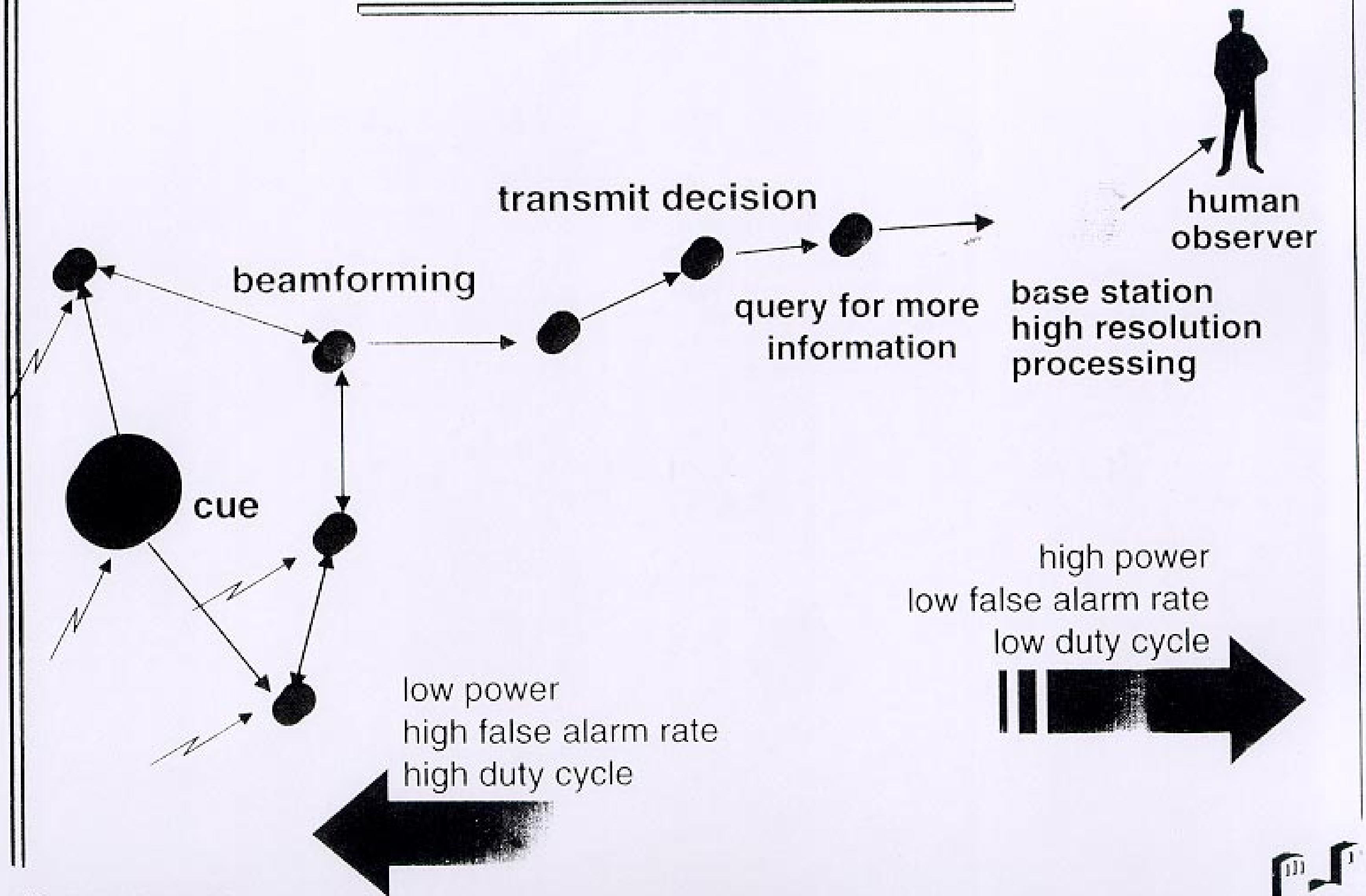
$$x(n) = \left[x_0(n)', \ldots, x_{R-1}(n)' \right], \qquad x_r(n) = \left[x_r(n), \ldots, x_r(n-L+1) \right]'$$

Self-Organizing Network

- Health monitoring, synchronization, routing, resource allocation, position location
- Low power prime driver: conventional networks aim for favorable latency / throughput
- Two modes:
  - start-up -- high connectivity/ identify all neighbors, determine logical hierarchy
  - steady state -- time division structure, use only lowest power connections (resources permitting)



Information Processing Hierarchy



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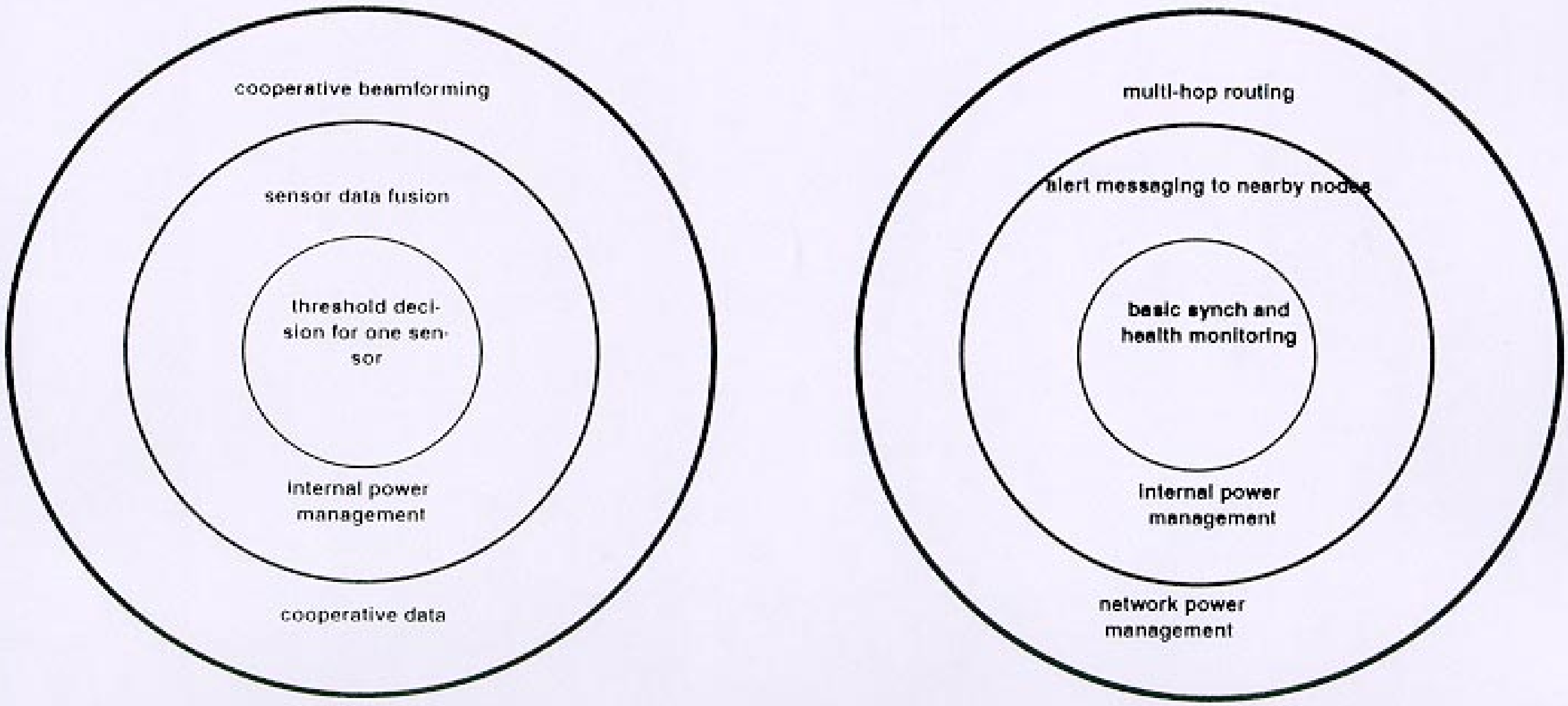
Embedded Functions

- Inner layers may also be stand-alone systems; developed first.

PROTOCOL LAYERING



Signal Processing

Networking

Wireless Sensor Nodes

- Computers are now networked, but most data entered by hand
- Next step: interface of computer networks to physical world by cheap, reliable sensor networks
- Eventual goal: with addition of actuation, computer networks which monitor and affect the physical world
- Enabling Technology: massive worldwide investment in IC fabrication; can leverage to create low cost sensors, actuators and RF components
- Integration of sensing, signal processing, communications and actuation on the same substrate will have broad applications
- New design paradigms: different latency, power consumption, speed tradeoffs; multidisciplinary research